Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE) prism spectrometer

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ABSTRACT

The FINESSE spectrometer design (0.45 to 5 µm at a resolution of greater than 80 at f/12) is placed in context by reviewing history of unit magnification relays and spectrometers. Related imaging spectrometers are also described. .

Keywords: Geometric optical design, spectrometers, prisms, and gratings

1. INTRODUCTION

Fast Infrared Exoplanet Spectroscopy Survey Explorer (FINESSE) is a mission proposed to characterize the atmospheres of the rapidly number of newly discovered words. It will measure the composition and temperature of exoplanet atmospheres. High precision 0.45 µm to 5 µm spectra are recorded over the exoplanet orbit and from those measurements the stellar emission is separated from the exoplanet emission on the dayside, exoplanet emission on the night side, and transmission. A 75 cm aperture telescope collects the photons.

Spectral stability is key to accurate exoplanet atmospheric measurements. In order to minimize thermal variation, observations are made from the second Lagrange point, L2. L2 is located 1.5 million kilometres directly 'behind' the Earth as viewed from the Sun, so the sun shield provides stable operation.

1.1 Spectrometer requirements

Table 1 summarizes the spectrometer requirements and goals. The driving requirements are to provide a spectral resolution of at least 80 and an image of the undispersed star for the fine guidance spectra. The goals are to maximize the throughput and minimizing the size (to reduce the cost and also maximize the stability).

The spectrometer is a point-spectrometer (not an imaging spectrometer), with the spectral resolution set by the Width at Half Maximum (FWHM) of the Point Spread Functions (PSF). Light enters the spectrometer through one of two redundant pinholes. The spacecraft attitude control system can place the image of the target star on either of the two pinholes, which can provides recovery from HgCdTe detector persistence effects and potential CCD damage in the region that maps to the pinholes. The pinhole size (about twice the Airy disk diameter at the longest wavelength) balances the noise contribution from background and pointing errors.

The radiometric stability must be better than 50 ppm over 8 hours. The all-aluminum telescope feeding the spectrometer is cooled (passively) for thermal IR background suppression and regulated at 125 K for mechanical stability. The spectrometer and detector are cooled (to 90 K and 70 K, respectively) by a dedicated passive radiator. To minimize the impact of inter- and intra-pixel variations of the QE, the star/exoplanet position is stabilized to better than 1/20th of a pixel using the spacecraft pointing (like Kepler). The PSF FWHM must be larger than 2 pixels at all wavelengths.

Table 1. Spectrometer specifications.

Wavelength range	0.45 to 5.0 µm	Array size	2048 x 2048
Resolution ($\lambda/\Delta\lambda$)	> 80	Efficiency	Maximize
FWHM	>2 pixels	Size	Minimize
Pixel size	18 µm	Operating temperature	90 K

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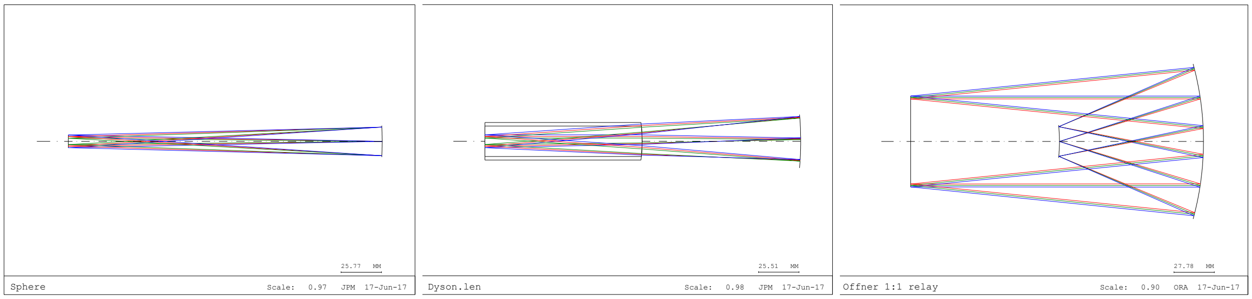


Figure 1. Unit magnification relays: sphere, Dyson, and Offner.

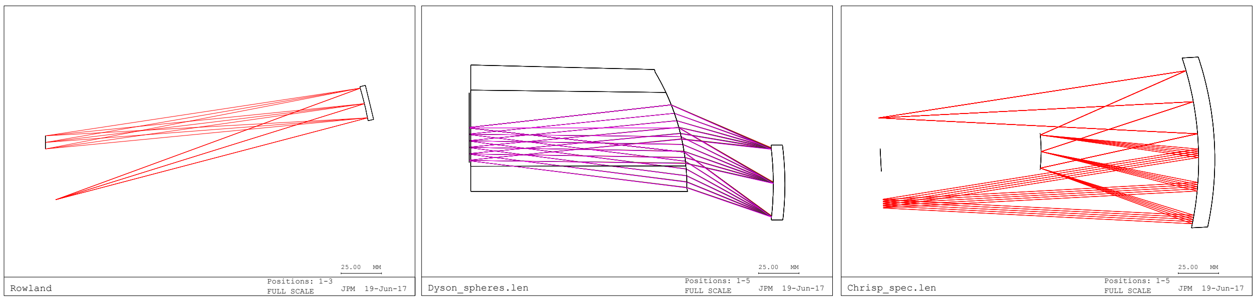


Figure 2. Unit magnification spectrometers: Rowland, Mertz, and Chrisp.

1.2 Unit magnification relays

This section reviews unit magnification relays, which have proven to be good starting points for compact spectrometers.

The simplest 1x relay is a sphere mirror (see Fig 1 left). The sphere is concentric with the object/image, so it introduces no spherical aberration. Since it is a mirror, it is free of chromatic aberrations. Spheres are effective over small fields.

In 1959, Dyson proposed an elegant relay consisting of a single thick plano-convex lens and spherical mirror (see Fig 1 center) [1]. Both elements are concentric with object/image plane, so spherical aberration is corrected. The focuses the top on the mirror and lens balances for the field curvature introduced by the mirror. The input is telecentric with the stop at the mirror, so the system is symmetric with no odd aberrations. Chromatic aberration is not corrected, which is not a limitation for the original microlithographic application. Unfortunately, there is ideally no clearance between the lens and the object/image plane and the objects and images are not well separated from each other. Wynne suggested splitting the refractive lens to increase the correction [2].

An Offner relay consists of 3 concentric spherical mirrors (see Fig 1 right) [3]. The input is telecentric with the stop at the secondary mirror. An Offner is all reflective, so chromatic aberrations are identically zero. Since the mirrors are all concentric with the object/image, there is no spherical aberration. The secondary radius of curvature is half the radius of the primary and tertiary mirrors, so field curvature is corrected. The system is symmetric, so all the odd aberrations are identically zero. Third order astigmatism is corrected (higher order astigmatism often limits performance). The object and images are well separated, which is often advantageous. Dyson relays can work at faster speeds than Offner relays. Wynne suggested adding a refractive corrector to the Offner to increase the field of view [2]. Replacing the spherical primary/tertiary mirror with a free-form mirror (largely astigmatic) improves the correction.

1.3 Unit magnification grating spectrometers

This section reviews grating spectrometers based on unit magnification relays. They have uniform spectral resolution, which is often advantageous. The chief disadvantage is that the diffraction efficiency decreases as the spectral band increases.

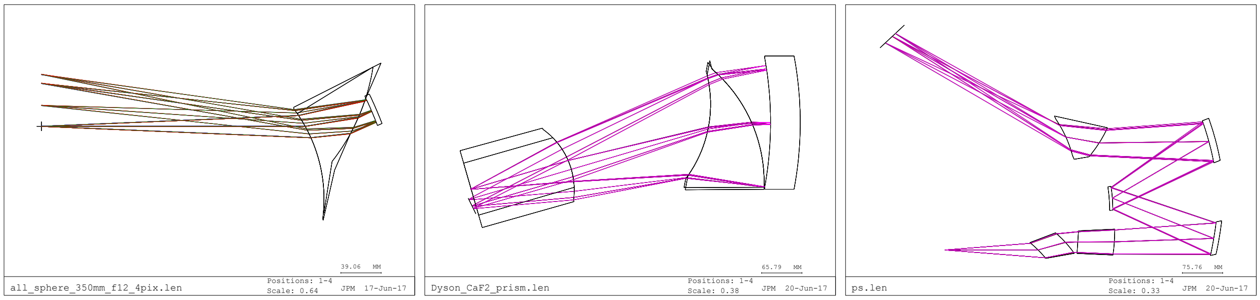


Figure 3. Unit magnification prism spectrometers: Fery, Lobb, and Lobb.

Rowland first proposed an optical spectrometer utilizing a single concave diffraction grating in 1882 with the entrance slit, exit slit, and mirror center of curvature all on the same circle (see Fig 2 left). Rowland‘s spectrometer combined the advantages of the plane diffraction grating with the focusing properties of a concave mirror. In 1977, Mertz proposed a concentric spectrometers with a grating on the spherical mirror of a Dyson relay to form a concentric spectrometer [5]. The same paper also showed a design from Thevenon with a grating on the convex mirror of an Offner spectrometer operating near Littrow. Light from the secondary was directed nearly back on itself to the primary, which formed an image of the dispersed light near the entrance slit.

In 1996, Chrisp proposed using the Offner spectrometer with a weaker grating than Thevenon [6]. With less diffraction, the light diffracted back to the tertiary on the opposite side of the optical axis (unlike the Thevenon spectrometer). This design has been a popular configuration, with the slit and image well separated for packaging.

1.4 Unit magnification prism spectrometers

Prism based spectrometers have about 3x more throughput than grating spectrometers over the FINESSE’s spectral band, which trumps the disadvantages (e.g. non-uniform spectral resolution) for photon limited applications like FINESSE.

In 1911, Fery replaced the grating in a Rowland circle spectrometer with a prism with two spherical surfaces [7]. The second surface was reflective. Coma and astigmatism limit performance. In 1983, Wildman used toroidal surfaces to reduce the astigmatism [8]. Moving the reflective surface from the prism to a spherical mirror increases allows one or both of the prism surfaces to be aplanatic or quasi aplanatic [9-11]. With aplanatic surfaces, the coma and astigmatism can be corrected at one wavelength. Furthermore with an aplanatic prism, the chromatic variations of spherical aberration and astigmatism are of opposite sign at input and output faces of each prism. Chromatic variation of coma limits the correction, since the spectral variation in third-order coma produced by each surface is proportional to the dispersive spread produced by the surface.

Lobb designed a spectrometer based on a Dyson relay using the same principles as the Offner spectrometer [12]. In the Offner-Lobb and Dyson-Lobb prism based spectrometers, all the surfaces were roughly rotationally symmetric about the line defined by the object and image.

In 1998, Bittner proposed an Offner based prism spectrometer with the convex secondary mirror replaced by a Fery prism with a reflective second surface [11]. In the same year, Lobb proposed a better corrected Offner based prism spectrometer with one Fery prism in object space and one in image space [12]. With one prism in diverging light introducing astigmatism and one in converging light astigmatism of the opposite sign, the field dependence of the astigmatism can be corrected. Lobb also teaches the use of a third “field prism” to correct the curvature of the image of the slit (often referred to as smile).

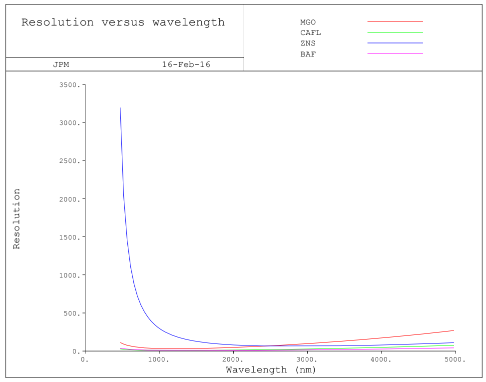


Figure 4. Resolution for a sample prism for materials that transmit over the required spectral band.

2. FINESSE SPECTROMETER

A prism spectrometer was selected to maximize efficiency. Over the 0.45-5 µm spectral band, there are only a few commonly available optical materials shown in Fig. 4. Zinc sulfide's dispersion is mostly in the visible and near IR. MgO bas excellent dispersion, but not commonly available. BaF has less dispersion than CaF2 and is harder to work, so we chose CaF2.

First a classic Warren spectrometer was designed using all spherical surfaces, but an RMS spot size of only 169 µm could be achieved at f/12 speed, with the FINESSE dispersion, and under the constraint for the system to be less than 350 mm long. Astigmatism and coma dominated the residual aberrations. Replacing the spherical mirror with a y-toroid, allowed a reduction in the RMS wavefront error to 100 µm (still a factor of ~5 too large).

The next step up in complexity in the classical prism spectrometers is an Offner-Lobb or Dyson-Lobb prism spectrometer. Both configurations can provide the required resolution. However, the Offner-Lobb suffers from a large separation between the object and spectra, which leads to a larger size (which is bad for stability and cost) and makes it challenging to form both dispersed and undispersed (for fine guidance) images on the same detector. The Dyson-Lobb is more compact, but the lack of clearance between the Dyson lens and both the object and image makes forming dispersed and undispersed images on the same focal planes challenging. FINESSE needs spectrometer design with the correction of an Offner-Lobb or Dyson-Lobb, which readily accommodate dispersed and undispersed images on the same focal planes. Since FINESSE has a small field, we examined some alternate configurations.

We started with the Dyson-Lobb configuration, with an aplanatic prism. During optimization, the mirror was kept approximately concentric with the pinhole/spectral plane to remove the spherical aberration. Keeping the system telecentric and unit magnification, eliminates odd aberrations at one wavelength. Balancing the powers of the refractive and reflective elements corrects the field curvature. With two pinholes covering a smaller field of view than a true imaging spectrometer, the astigmatism correction is less demanding. The thick plano-convex lens in the Dyson was replaced by an off-axis portion of a comparative thin lens. Figure 5 shows the design and the spot sizes. This design meets all of the FINESSE requirements with all spherical surfaces, but the number of uncoated surfaces diminishes throughput.

In order to improve the throughput, we went back to the single prism design and reoptimized with a freeform mirror. Figure 6 shows the resulting design and the spot sizes. The 30 mm diameter free form prism will be more expensive than the sphere, but this will be partially offset by having one fewer element to buy, mount, and align. The freeform spectrometer is more cost effective than the alternative (i.e. increasing the telescope aperture diameter from 75 cm to 80 cm).

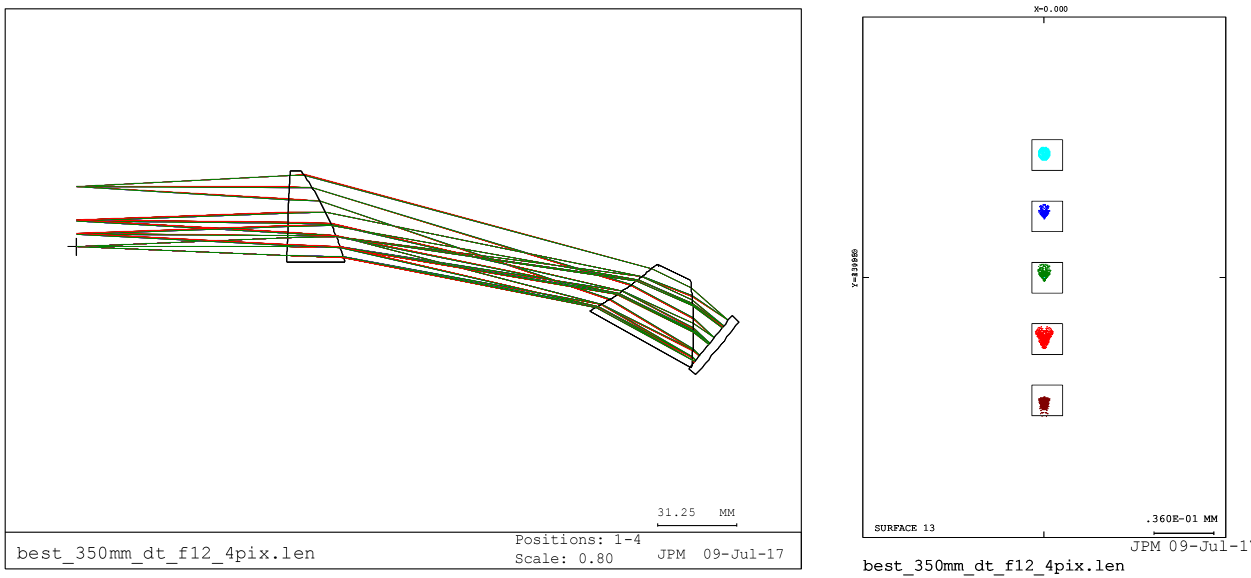


Figure 5. All spherical option for FINESSE. The spots are less than 6 µm rms.

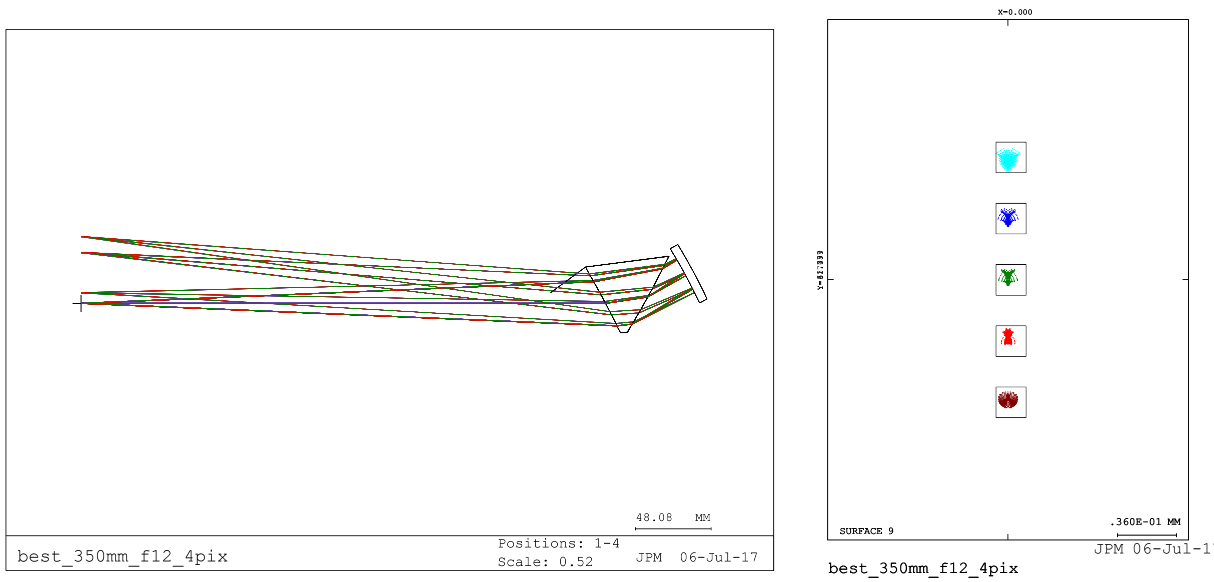


Figure 6. FINESSE spectrometer with a single freeform mirror. The spots are less than 7 µm rms.

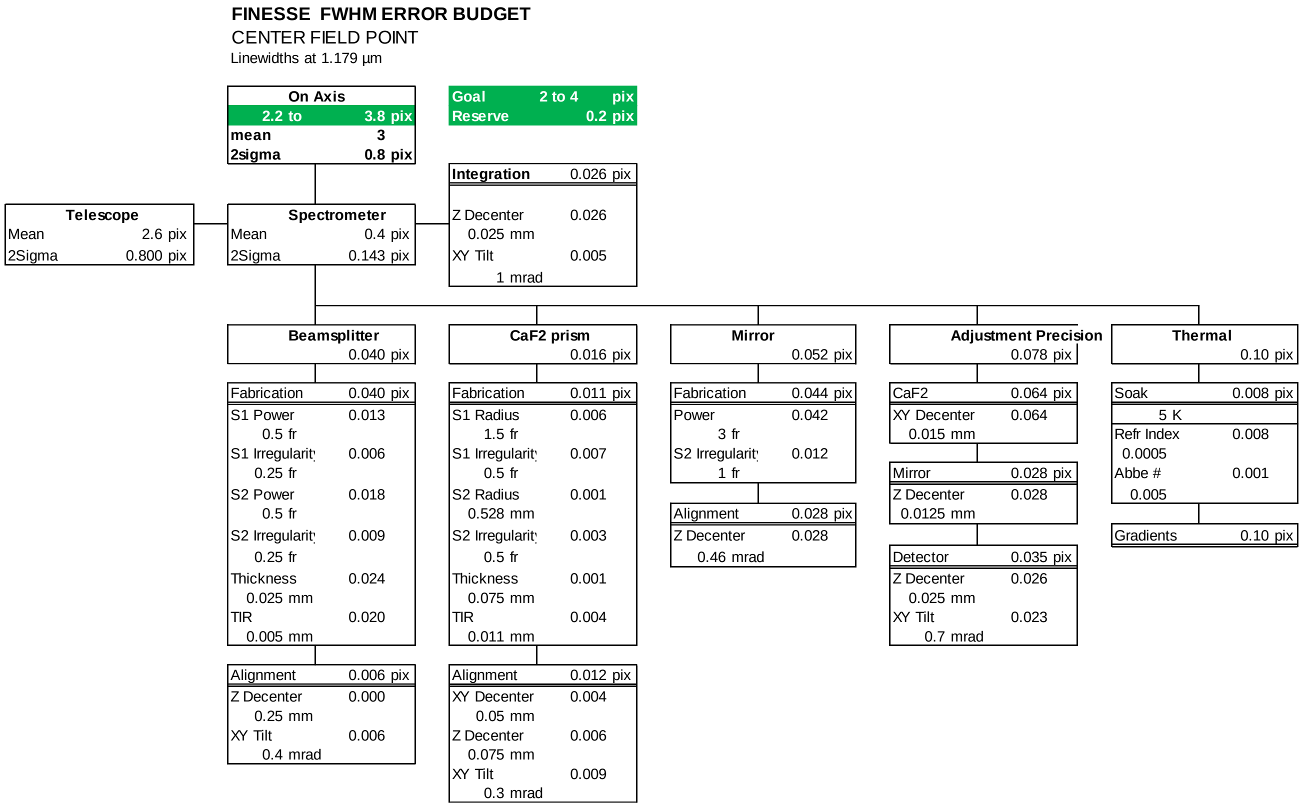


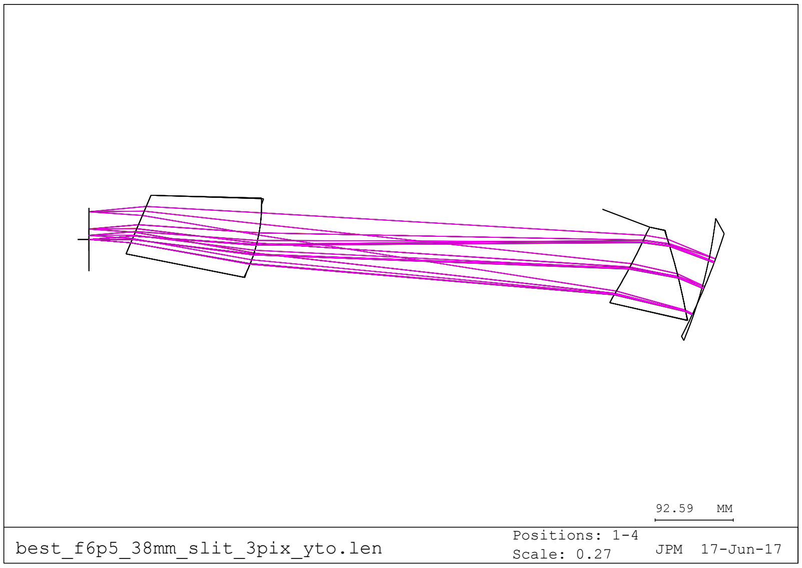
Figure 7. Preliminary error budget for the Full Width at Half Maximum (FWHM) for the instrument spectral linewidth.

3. ERROR BUDGET

FINESSE performance is driven by FWHM required to meet the spectral resolution specification, so the error budget uses this metric. The requirements are double sided with both minimum and maximum values. The strategy was to let the telescope tolerances drive the performance (cryogenic performance will be harder to achieve on big Al mirrors than small spectrometer optics). All performance predictions are 2σ. Figure 8 shows the error budget for the spectrometer. Thermally induced errors (from deviations from the nominal temperature and gradients) have the largest allocations. The prism tolerances are a factor of 2 looser than Optimax has previously delivered on comparable prisms with spherical surfaces.

4. FINESSE ALIGNMENT

The system will be respaced based measurements of the as-built elements. A Coordinate Measuring Machine (CMM) will be used to place tooling balls at the locations that correspond to the ideal locations of the centers of curvature of the prism to within ±5 µm. These balls will establish the coordinate system for subsequent alignments. The prism will be bonded into its flexure cell. Using a long working distance objective, the prism will then be aligned to the tooling balls. The aluminum mirror will then be installed into the structure using its precision mounting features, diamond turned at the same time as its optical surface without removing the part from the machine. Next the lens will be mounted into its flexure cell and installed into the structure using the CMM. Final adjustments of the focal plane focus, tip/tilt, lens transverse position, and mirror axial position are adjusted to maximize image quality for all the wavelengths. CMM based alignment of asymmetric system have been previously be demonstrated by JPL on Pressure Modulated Infrared Radiometer (PMIRR).



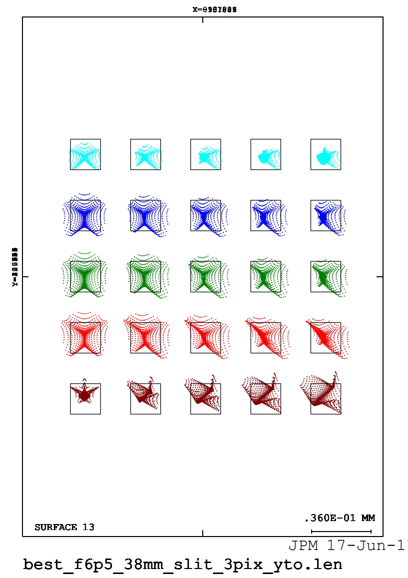
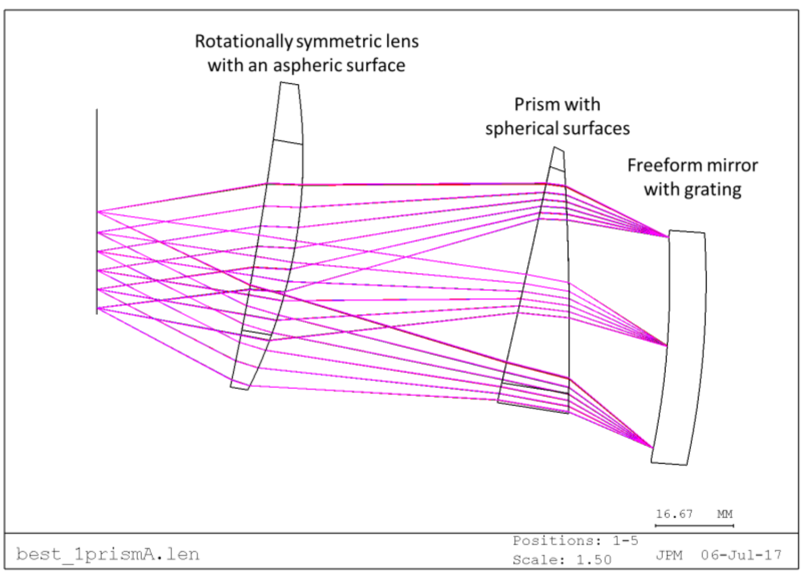


Figure 8. Imaging spectrometer with a 37 mm slit for the FINESSE spectral band operating at f/6.5. The spot diameters are less than 15 µm rms.



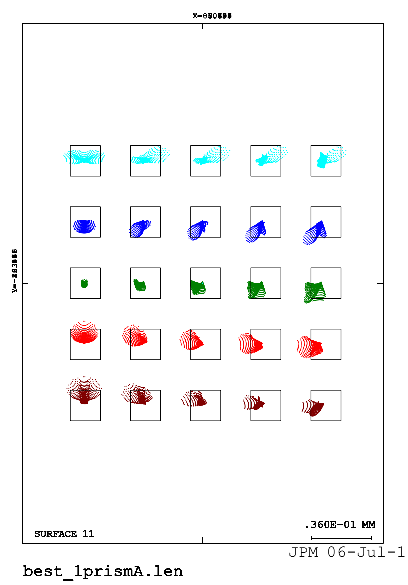


Figure 9. IR Grating spectrometer with CdTe elements. The spot diameters are less than 9 µm rms across the sensor.

5. SPIN-OFF DESIGNS

While FINESSE uses a slow point spectrometer, the same principles can be used effectively to design slit spectrometers as demonstrated in this section.

First, consider the case of an imaging spectrometer that covers the same spectral range as FINESSE, but operates at f/6.5 and with a 37 mm long slit. The starting point was the spectrometer with two refractive elements shown in Fig 5, with a y-toroid mirror replacing the spherical mirror to control field constant aberrations. Figure 8 shows resulting the design and the spot diagrams. Smile and keystone are corrected to 0.4 µm and 0.6 µm, respectively.

Next, consider the case of an imaging spectrometer that covers 11-16.5 µm with a 15 mm slit and 15 mm of dispersion operating at f/1.7. We started with the imaging spectrometer design shown in Fig. 8 and converted the elements to CdTe for good transmission. The high spectral resolution suggests the use of grating, so the mirror was converted to a grating to provide most of the dispersion. While the nominal design had 11 µm diameter spots with just a single freeform surface, tolerance analysis showed that the system would be easier to build, if the element nearest the focal plane included a rotationally symmetric asphere. Figure 9 shows resulting the design and the spot diagrams.

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